71. Pseudoscalar and Pseudovector Mesons in the 1400 MeV Region

Revised August 2017 by C. Amsler (Stefan Meyer Institute for Subatomic Physics, Vienna) and A. Masoni (INFN Cagliari).

This minireview deals with some of the 0^{-+} and 1^{++} mesons reported in the 1200–1500 MeV region, namely the $\eta(1405)$, $\eta(1475)$, $f_1(1285)$ $f_1(1420)$, $a_1(1420)$ and $f_1(1510)$. The first observation of a pseudoscalar resonance around 1400 MeV – the $\eta(1440)$ – was made in $p\overline{p}$ annihilation at rest into $\eta(1440)\pi^+\pi^-$, $\eta(1440) \to K\overline{K}\pi$ [1]. This state was reported to decay into $a_0(980)\pi$ and $K^*(892)\overline{K}$ with roughly equal contributions. The $\eta(1440)$ was also observed in radiative $J/\psi(1S)$ decay into $K\overline{K}\pi$ [2–4] and $\gamma\rho$ [5]. However, two pseudoscalars are now reported in this mass region, the $\eta(1405)$ and $\eta(1475)$. The former decays mainly through $a_0(980)\pi$ (or direct $K\overline{K}\pi$) and the latter mainly to $K^*(892)\overline{K}$.

The simultaneous observation of two pseudoscalars is reported in three production mechanisms: π^-p [6,7]; radiative $J/\psi(1S)$ decay [8,9]; and $\overline{p}p$ annihilation at rest [10–13]. All of them give values for the masses, widths, and decay modes that are in reasonable agreement. However, Ref. [9] favors a state decaying into $K^*(892)\overline{K}$ at a lower mass than the state decaying into $a_0(980)\pi$. In $J/\psi(1S)$ radiative decay, the $\eta(1405)$ decays into $K\overline{K}\pi$ through $a_0(980)\pi$, and hence a signal is also expected in the $\eta\pi\pi$ mass spectrum. This was indeed observed by MARK III in $\eta\pi^+\pi^-$ [14], which reported a mass of 1400 MeV, in line with the existence of the $\eta(1405)$ decaying into $a_0(980)\pi$.

BESII [15] observes an enhancement in $K^+K^-\pi^0$ around 1.44 GeV in $J/\psi(1S)$ decay, recoiling against an ω (but not a ϕ) without resolving the presence of two states nor performing a spin-parity analysis, due to low statistics. This state could also be the $f_1(1420)$ (see below). On the other hand, BESII observes $\eta(1405) \to \eta\pi\pi$ in $J/\psi(1S)$ decay, recoiling against an ω [16]. A single unresolved broad peak is also observed by BESIII in the decay $\psi(2S) \to \omega K^*K$ which could be due to $\eta(1405)$, $\eta(1475)$ and $f_1(1420)$ [17].

The $\eta(1405)$ is also observed in $\overline{p}p$ annihilation at rest into $\eta\pi^+\pi^-\pi^0\pi^0$, where it decays into $\eta\pi\pi$ [18]. The intermediate $a_0(980)\pi$ accounts for roughly half of the $\eta\pi\pi$ signal, in agreement with MARK III [14] and DM2 [4].

However, the issue remains controversial as to whether two pseudoscalar mesons really exist. According to Ref. [19] the splitting of a single state could be due to nodes in the decay amplitudes which differ in $\eta\pi\pi$ and $K^*(892)\overline{K}$. Based on the isospin-violating decay $J/\psi(1S) \to \gamma 3\pi$ observed by BESIII [20] the splitting could also be due to a triangular singularity mixing $\eta\pi\pi$ and $K^*(892)\overline{K}$ [21–22]. However, in a further paper [23], using the approach of [21], the authors concluded that the BESIII results can be reproduced either with the $\eta(1405)$ or the $\eta(1475)$, or by a mixture of these two states.

The $\eta(1295)$ has been observed by four π^-p experiments [7,24–26], and evidence is reported in $\overline{p}p$ annihilation [27–29]. In $J/\psi(1S)$ radiative decay, the $\eta(1295)$ signal is evident in the 0^{-+} $\eta\pi\pi$ wave of the DM2 data [9]. Also BaBar [30] reports evidence for a signal around 1295 MeV in B decays into $\eta\pi\pi K$. Nonetheless, the existence of the

$\eta(1295)$ is questioned in Refs. [19] and [31] in which the authors claim the existence of a single pseudoscalar meson at 1440 MeV, the first radial excitation of the η. This conclusion is mainly based on the analysis of the annihilation $\bar{p}p \to 4\pi\eta$ with Crystal Barrel data [32].

Considering that the $\eta(1295)$ has been reported by several experiments, using different production mechanisms, we shall assume that this state is established. The $\eta(1475)$ could then be the first radial excitation of the η', with the $\eta(1295)$ being the first radial excitation of the η. Ideal mixing, suggested by the $\eta(1295)$ and $\pi(1300)$ mass degeneracy, would then imply that the second isoscalar in the nonet is mainly $s\bar{s}$, and hence couples to $K^*\overline{K}$, in agreement with properties of the $\eta(1475)$. Also, its width matches the expected width for the radially excited $s\bar{s}$ state [33,34]. A study of radial excitations of pseudoscalar mesons [35] favors the $s\bar{s}$ interpretation of the $\eta(1475)$. However, due to the strong kinematical suppression the data are not sufficient to exclude a sizeable $s\bar{s}$ admixture also in the $\eta(1405)$.

The $K\overline{K}\pi$ and $\eta\pi\pi$ channels were studied in $\gamma\gamma$ collisions by L3 [36]. The analysis led to a clear $\eta(1475)$ signal in $K\overline{K}\pi$, decaying into $K^*\overline{K}$, very well identified in the untagged data sample, where contamination from spin 1 resonances is not allowed. At the same time, L3 [36] did not observe the $\eta(1405)$, neither in $K\overline{K}\pi$ nor in $\eta\pi\pi$. The observation of the $\eta(1475)$, combined with the absence of an $\eta(1405)$ signal, strengthens the two-resonances hypothesis. Since gluonium production is presumably suppressed in $\gamma\gamma$ collisions, the L3 results [36] suggest that $\eta(1405)$ has a large gluonic content (see also Refs. [37] and [38]) .

The L3 result is somewhat in disagreement with that of CLEO-II, which did not observe any pseudoscalar signal in $\gamma\gamma \to \eta(1475) \to K_S^0 K^\pm \pi^\mp$ [39]. However, more data are required. Moreover, after the CLEO-II result, L3 performed a further analysis with full statistics [40], confirming their previous evidence for the $\eta(1475)$. The CLEO upper limit [39] for $\Gamma_{\gamma\gamma}(\eta(1475))$, and the L3 results [40], are consistent with the world average for the $\eta(1475)$ width.

BaBar [30] also reports the $\eta(1475)$ in B decays into $K\bar{K}^*K$ with the $\eta(1475) \to K\bar{K}^*$ recoiling against a K, but upper limits only are given for the $\eta(1405)$. As mentioned above, in B decays into $\eta\pi\pi K$ the $\eta(1295) \to \eta\pi\pi$ is observed while only upper limits are given for the $\eta(1405)$. The $f_1(1420)$ (and $f_1(1285)$) are not seen.

The gluonium interpretation for the $\eta(1405)$ is not favored by lattice gauge theories which predict the 0^{-+} state above 2 GeV [41,42] (see also the article on the "Quark model" in this issue of the Review). However, the $\eta(1405)$ is an excellent candidate for the 0^{-+} glueball in the fluxtube model [43]. In this model, the 0^{++} $f_0(1500)$ glueball is also naturally related to a 0^{-+} glueball with mass degeneracy broken in QCD. Also, Ref. [44] shows that the pseudoscalar glueball could lie at a lower mass than predicted from lattice calculation. In this model the $\eta(1405)$ appears as the natural glueball candidate, see also Refs. [45–47]. A detailed review of the experimental situation is available in Ref. 48.

Let us now deal with the 1^{++} mesons. The pseudovector nonet is believed to consist of the isovector $a_1(1260)$, the isoscalars $f_1(1285)$ and $f_1(1420)$, and the K_{1A}, which

is a mixture of about 50% $K_1(1270)$ and 50% $K_1(1400)$. (This last property prevents a straightforward calculation of the nonet mixing angle via the mass formulae.) The $f_1(1285)$ could also be a $K^*\overline{K}$ molecule [49] or as a tetraquark state [50] and the $f_1(1420)$ a $K^*\overline{K}$ molecule, due to the proximity of the $K^*\overline{K}$ threshold [51]. LHCb has analyzed the decays $\overline{B}^0$ and $\overline{B}_s^0 \to J/\psi(1S)f_1(1285)$ and determined the nonet mixing angle to be consistent with a mostly $u\overline{u} + d\overline{d}$ structure [52] without specifying the identity of its isoscalar partner. This is consistent with earlier determinations assuming the $f_1(1420)$ as the isoscalar partner [53] and the ratio of $\overline{B}^0/\overline{B}_s^0$ decay rates excludes the tetraquark interpretation of this state [52].

The $f_1(1420)$, decaying into $K^*\overline{K}$, was first reported in $\pi^- p$ reactions at 4 GeV/c [54]. However, later analyses found that the 1400–1500 MeV region was far more complex [55–57]. A reanalysis of the MARK III data in radiative $J/\psi(1S)$ decay into $K\overline{K}\pi$ [8] shows the $f_1(1420)$ decaying into $K^*\overline{K}$. A C=+1 state is also seen in tagged $\gamma\gamma$ collisions (*e.g.*, Ref. [58]) .

In $\pi^- p \to \eta\pi\pi n$ charge-exchange reactions at 8–9 GeV/c the $\eta\pi\pi$ mass spectrum is dominated by the $\eta(1440)$ and $\eta(1295)$ [24,59], and at 100 GeV/c Ref. [25] reports the $\eta(1295)$ and $\eta(1440)$ decaying into $\eta\pi^0\pi^0$ with a weak $f_1(1285)$ signal, and no evidence for the $f_1(1420)$.

Axial (1^{++}) mesons are not observed in $\overline{p}p$ annihilation at rest in liquid hydrogen, which proceeds dominantly through S-wave annihilation. However, in gaseous hydrogen, P-wave annihilation is enhanced and, indeed, Ref. [11] reports $f_1(1420)$ decaying into $K^*\overline{K}$. The $f_1(1420)$, decaying into $K\overline{K}\pi$, is also seen in pp central production, together with the $f_1(1285)$. The latter decays via $a_0(980)\pi$, and the former only via $K^*\overline{K}$, while the $\eta(1440)$ is absent [60,61]. The $K_S^0 K_S^0 \pi^0$ decay mode of the $f_1(1420)$ establishes unambiguously C=+1. On the other hand, there is no evidence for any state decaying into $\eta\pi\pi$ around 1400 MeV, and hence the $\eta\pi\pi$ mode of the $f_1(1420)$ must be suppressed [62].

The COMPASS Collaboration has recently reported an isovector state at 1414 MeV, the $a_1(1420)$ [63]. This relatively narrow state ($\simeq$150 MeV) is produced by diffractive dissociation with 190 GeV pions in $\pi N \to 3\pi N$, decays into $f_0(980)\pi \to 3\pi$ (P-wave) and has therefore the quantum numbers $(I^G)J^{PC} = (1^-)1^{++}$. The pseudovector nonet already contains the established $a_1(1260)$ as the $I = 1$ state. As mentioned above, the $f_1(1420)$ has been interpreted as a $K^*\overline{K}$ molecule [51]. The new $a_1(1420)$ could be its isovector partner. Arguments favoring the $f_1(1420)$ being a hybrid $q\overline{q}g$ meson [64] or a four-quark state [65] were also put forward. The $q\overline{q}$ state would then remain to be identified, with the $f_1(1510)$ (see below) as a candidate. However, an alternative explanation is suggested in Ref. [66] in which the authors claim a single 1^{++} isovector around 1400 MeV, leading to two peaks in the 3π mass spectrum, depending on the production mechanism, $\rho\pi$ for the $a_1(1260)$ and $f_0(980)\pi$ for the $a_1(1420)$.

We now turn to the experimental evidence for the $f_1(1510)$. The $f_1(1510)$ was seen in $K^- p \to \Lambda K\overline{K}\pi$ at 4 GeV/c [67], and at 11 GeV/c [68]. Evidence is also reported in $\pi^- p$ at 8 GeV/c, based on the phase motion of the 1^{++} $K^*\overline{K}$ wave [57]. A somewhat broader 1^{++} signal is also observed in $J/\psi(1S) \to \gamma\eta\pi^+\pi^-$ [69] as well as a small signal

in $J/\psi(1S) \to \gamma\eta'\pi^+\pi^-$, attributed to the $f_1(1510)$ [70].

The absence of $f_1(1420)$ in K^-p [68] argues against the $f_1(1420)$ being the $s\bar{s}$ member of the 1^{++} nonet. However, the $f_1(1420)$ was reported in K^-p but not in π^-p [71], while two experiments do not observe the $f_1(1510)$ in K^-p [71,72]. The latter is also not seen in central collisions [61], nor $\gamma\gamma$ collisions [73], although, surprisingly for an $s\bar{s}$ state, a signal is reported in 4π decays [74]. These facts led to the conclusion that $f_1(1510)$ was not well established [75].

Summarizing, there is evidence for two isovector 1^{++} states in the 1400 MeV region, the $a_1(1260)$ and $a_1(1420)$, which cannot be both $q\bar{q}$ states. These two states could stem from the same pole, or the latter be exotic (tetraquark or hybrid) or a molecular state. The $f_1(1285)$ and the $f_1(1420)$ are well known but their nature ($q\bar{q}$, tetraquark or molecular) remains to be established. In the 0^{-+} sector there is evidence for two pseudoscalars in the 1400 MeV region, the $\eta(1405)$ and $\eta(1475)$, decaying into $a_0(980)\pi$ and $K^*\overline{K}$, respectively. Alternatively, these two structures could originate from a single pole. Doubts have been expressed on the existence of the $\eta(1295)$. The $f_1(1510)$ remains to be firmly established.

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